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R42/5600
12 December 1991

Mr. Mark Goldfarb
Palisades Institute for Research Services Inc.
Power 92
2011 Crystal Drive, Suite 307
Arlington, VA 22202

Dear Mr. Goldfarb:

Submitted herewith for inclusion in the 1992 Power Modulator Symposium is an abstract entitled "Study of Intense Relativistic Electron Beam Modulation by Wakefield Effects, by J. Miller, R. F. Schneider of the Naval Surface Warfare Center. This paper has been reviewed by cognizant naval authorities. It is approved for public release.

Further correspondence intended for the authors should be directed to the attention of Dr. Ralph F. Schneider, Code R42, at the Naval Surface Warfare Center, White Oak, Silver Spring, Maryland 20903-5000.

Sincerely,

CARL W. LARSON, HEAD
Physics and Technology Division

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STUDY OF INTENSE RELATIVISTIC ELECTRON BEAM MODULATION BY WAKEFIELD EFFECTS*

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An experimental study has been undertaken in order to investigate plasma wakefield effects produced in intense electron beam propagation in a background plasma. A 2 MeV, 1 kA, electron beam is used for this experiment. A 50 cm diam., 3.6 m long drift tube is filled with a background gas, typically trimethylamine (TMA). This gas is ionized by electrons emitted from heated tungsten filaments which are biased at approximately -100 Volts. The resultant plasma density is fairly uniform and is adjustable in the range 10^8 to 5×10^9 cm^{-3}. A higher density Ion Focused Regime (IFR) channel for electron beam propagation is generated by KrF-laser (248 nm) ionization of the background TMA gas. The intense electron beam propagating on an IFR channel in this background plasma experiences wakefield effects due to the natural oscillations of the background plasma which are excited by the beam current risetime. The E_z component of the induced field is responsible for producing beam current modulation near the background plasma frequency. The results scale with plasma density as expected and current modulation is nearly complete for a certain parameter range. This technique may be amenable to a high power microwave generation technique analogous to the relativistic klystron. Detailed experimental results of beam modulation will be presented.

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PLASMA WAKEFIELD EFFECT

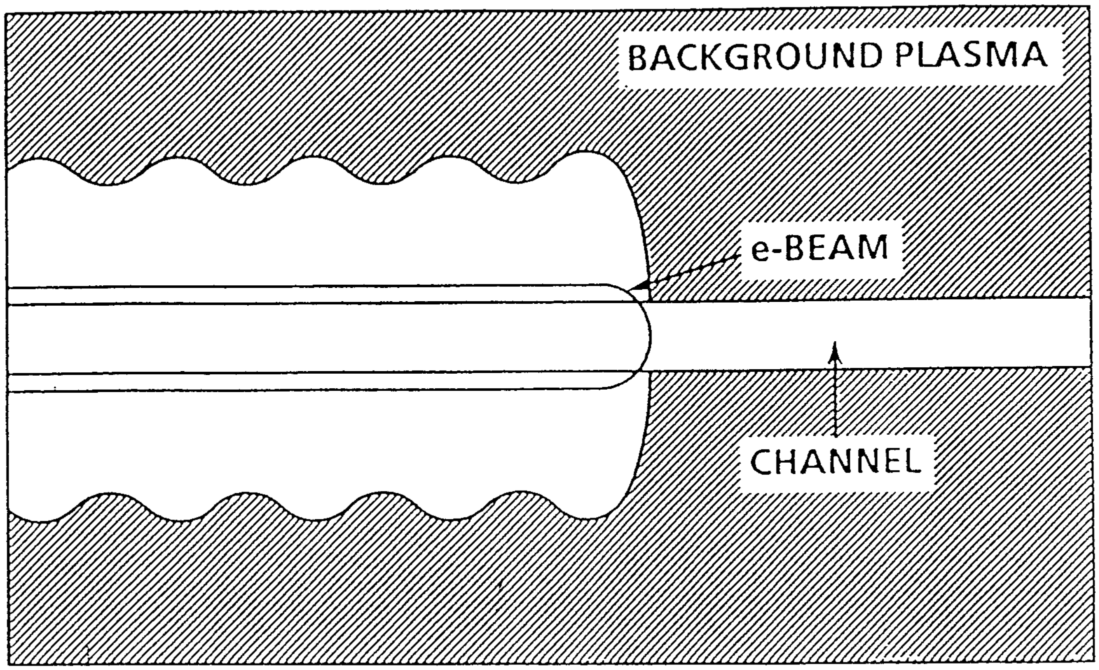
- THEORY AND SIMULATIONS HAVE PREDICTED THAT AN ELECTRON BEAM PROPAGATING IN A PLASMA BACKGROUND GIVES RISE TO A BEAM-PLASMA INTERACTION CALLED THE PLASMA WAKEFIELD EFFECT.

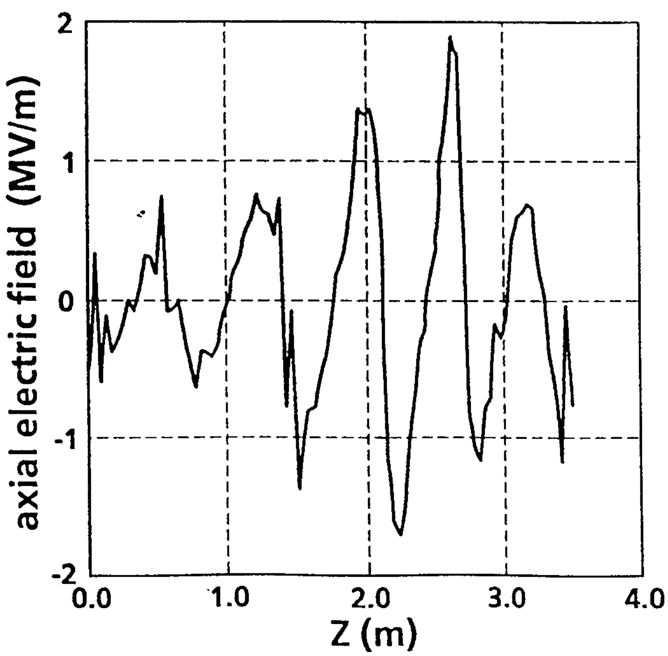
- THE FAST RISING INJECTED BEAM CURRENT EXPELS PLASMA ELECTRONS OUT TO THE CHARGE NEUTRALIZATION RADIUS. THIS INDUCES PLASMA OSCILLATIONS NEAR THE PLASMA FREQUENCY OF THE BACKGROUND PLASMA.

- THESE RADIAL PLASMA OSCILLATIONS PRODUCE A WAKEFIELD CHARACTERIZED BY LONGITUDINAL AND ACCOMPANYING RADIAL ELECTRIC FIELD OSCILLATIONS.

- RESONANT INTERACTION LEADS TO BEAM MODULATION AND EVENTUALLY ALLOWS PLASMA TO PENETRATE THE BEAM, LEADING TO ENHANCED EROSION AND LOSS OF BEAM CURRENT.

PLASMA WAKEFIELDS

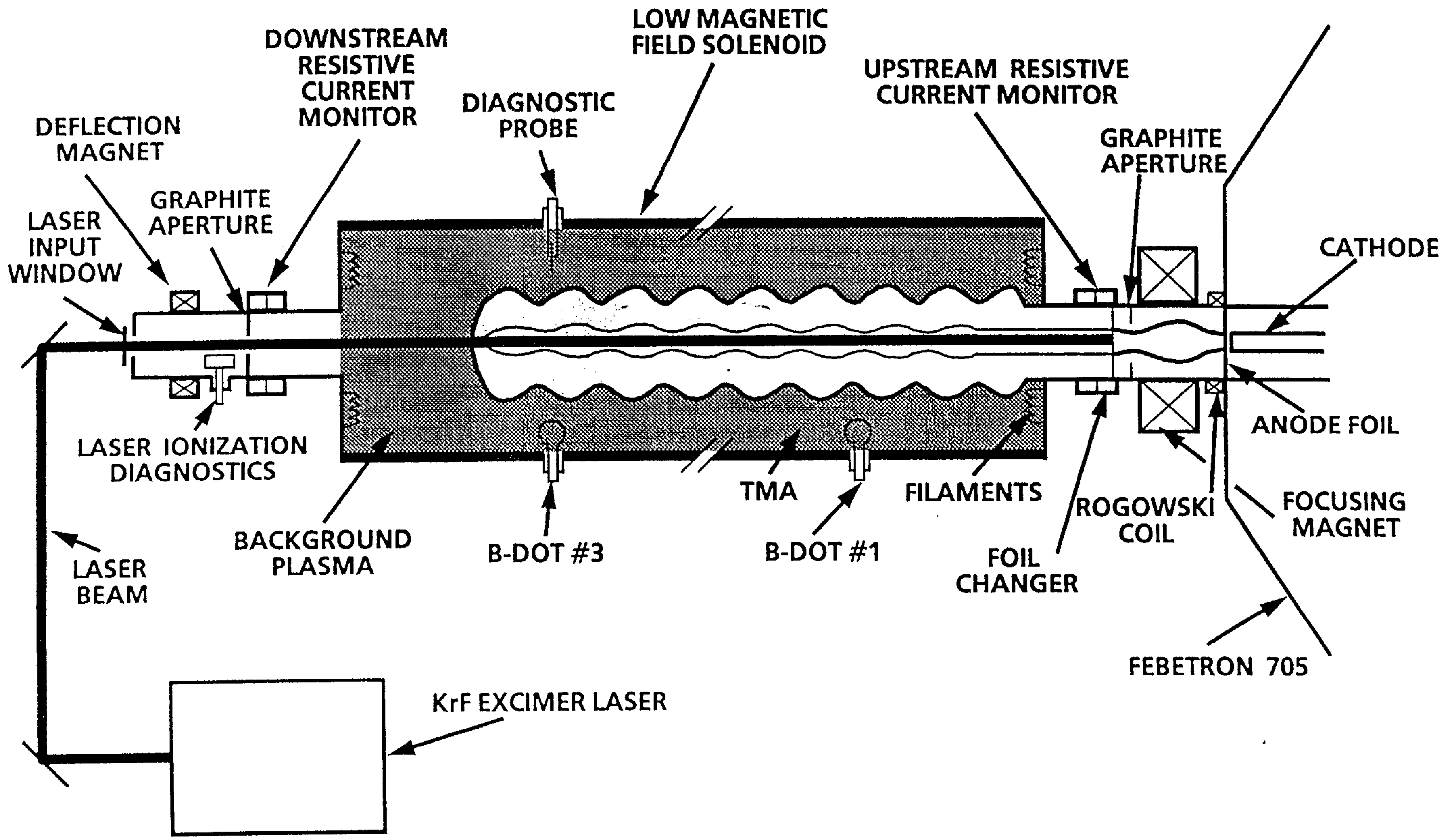




PLASMA WAKEFIELD EXPERIMENT

- FORM LOW DENSITY ($10^9 cm^{-3}$) BACKGROUND PLASMA BY HEATED FILAMENT DISCHARGE IN A 3.6m LONG, 0.5m DIAMETER DRIFT TUBE
- FORM CHANNEL FOR BEAM TO PROPAGATE USING KrF LASER IN TMA
- FIRE FEBETRON 705X INTO CHANNEL, BEAM PARAMETERS: 1kA, 2 MeV, 20nS
- MEASURE BACKGROUND PLASMA/ELECTRIC FIELD OSCILLATIONS AND MODULATION OF BEAM CURRENT, ENERGY

EXPERIMENTAL CONFIGURATION



EXPECTED OBSERVABLES AND DIAGNOSTICS

- MODULATION IN BEAM CURRENT
  - -B-DOTS, BEAM BUGS
- MODULATION IN BEAM ENERGY
  - -TIME RESOLVING ELECTRON ENERGY SPECTROMETER (TREES)

EXPERIMENTAL CONDITIONS

beam current, $I_b = 1$ kA

beam current risetime, $\tau = 4\text{-}5$ ns

beam energy, $V = 1.7$ MeV

beam radius, $r_b = 1.5$ cm

channel radius, $r_c = 1.5$ cm

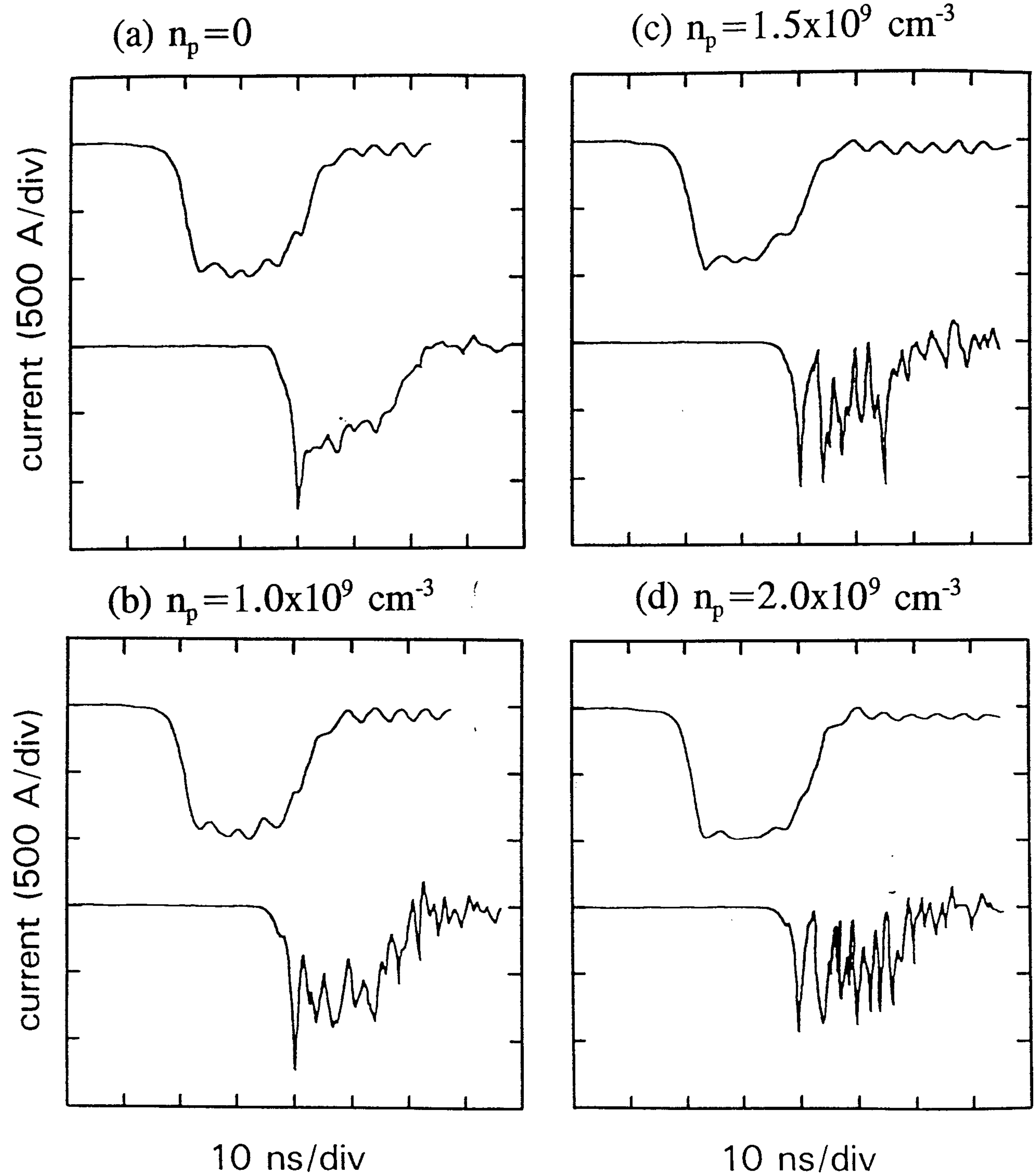
space charge neutralization fraction, $f_e = 0.9$

background plasma density, $n_p = 10^8 - 2\text{x}10^9$ cm^{-3}

g parameter, $g = n_p/n_b = 0.01 - 0.06$

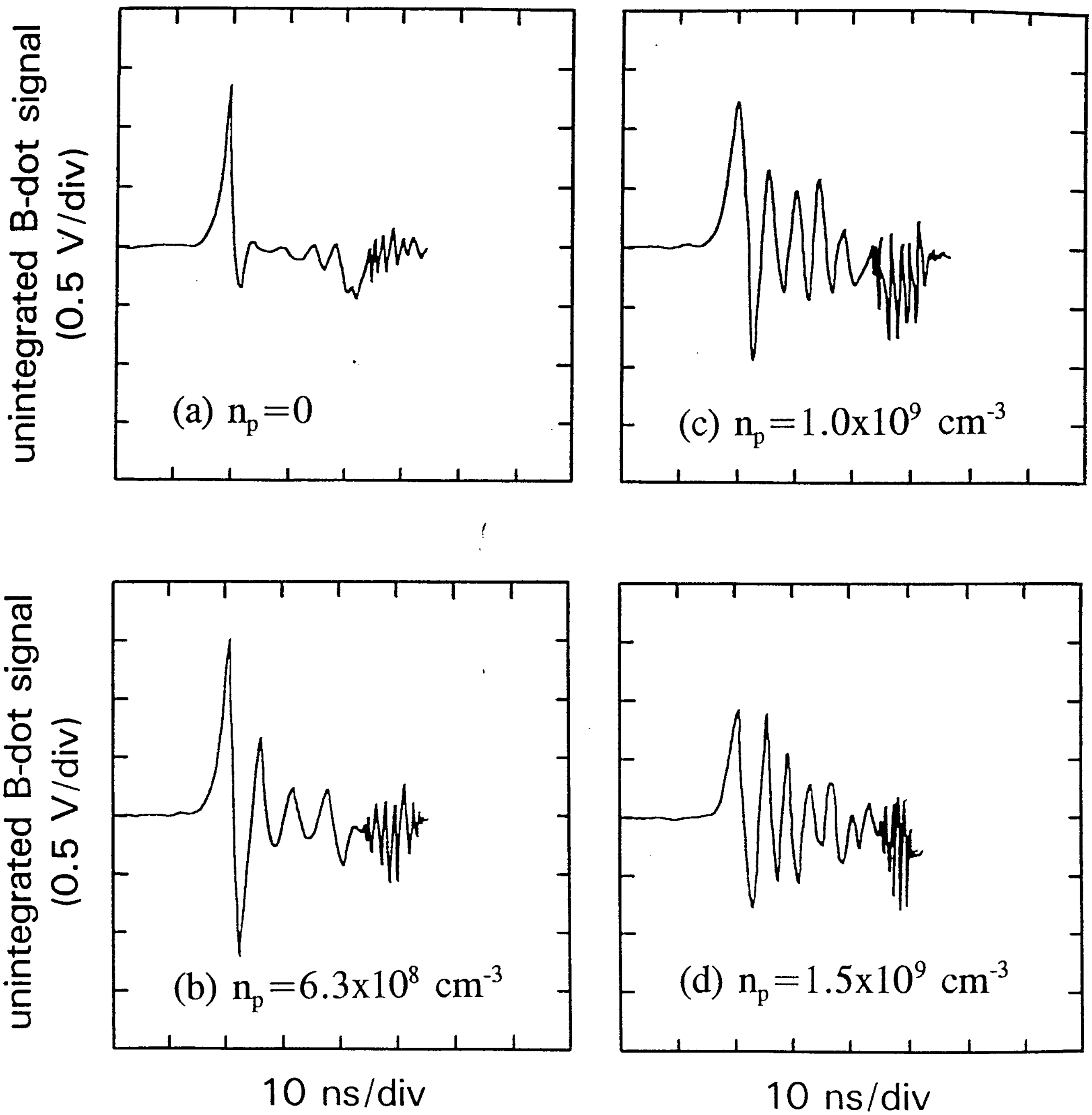
propagation distance, $z = 3.6$ m

EXPERIMENTAL CURRENT WAVEFORMS

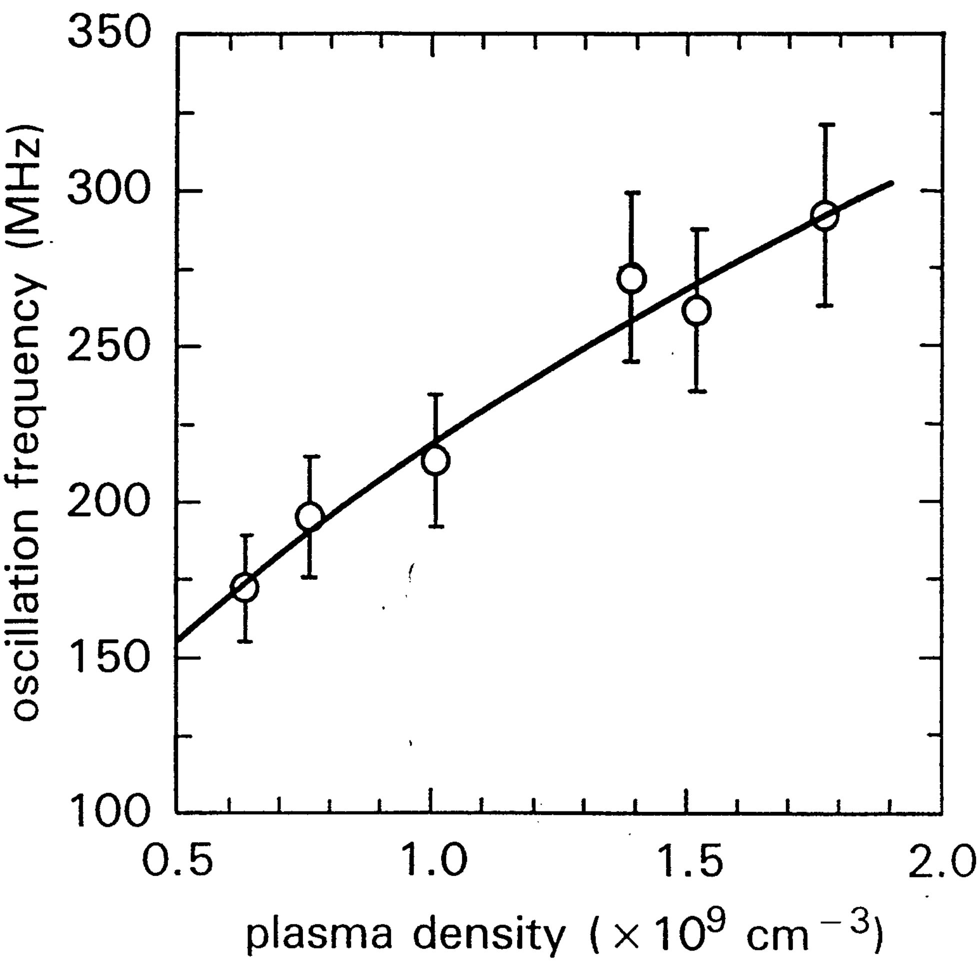


TOP (BOTTOM) WAVEFORM: CURRENT ENTERING (EXITING) THE PLASMA-FILLED TRANSPORT CHAMBER

EXPERIMENTAL B-DOT LOOP RESPONSE



B-DOT LOOP RESPONSE 0.9 M DOWNSTREAM FROM THE ENTRANCE TO THE TRANSPORT CHAMBER



Oscillation frequency from the unintegrated B-dot loop data as a function of the background plasma density. The solid line is a least-squares fit to $n_p^{1/2}$.

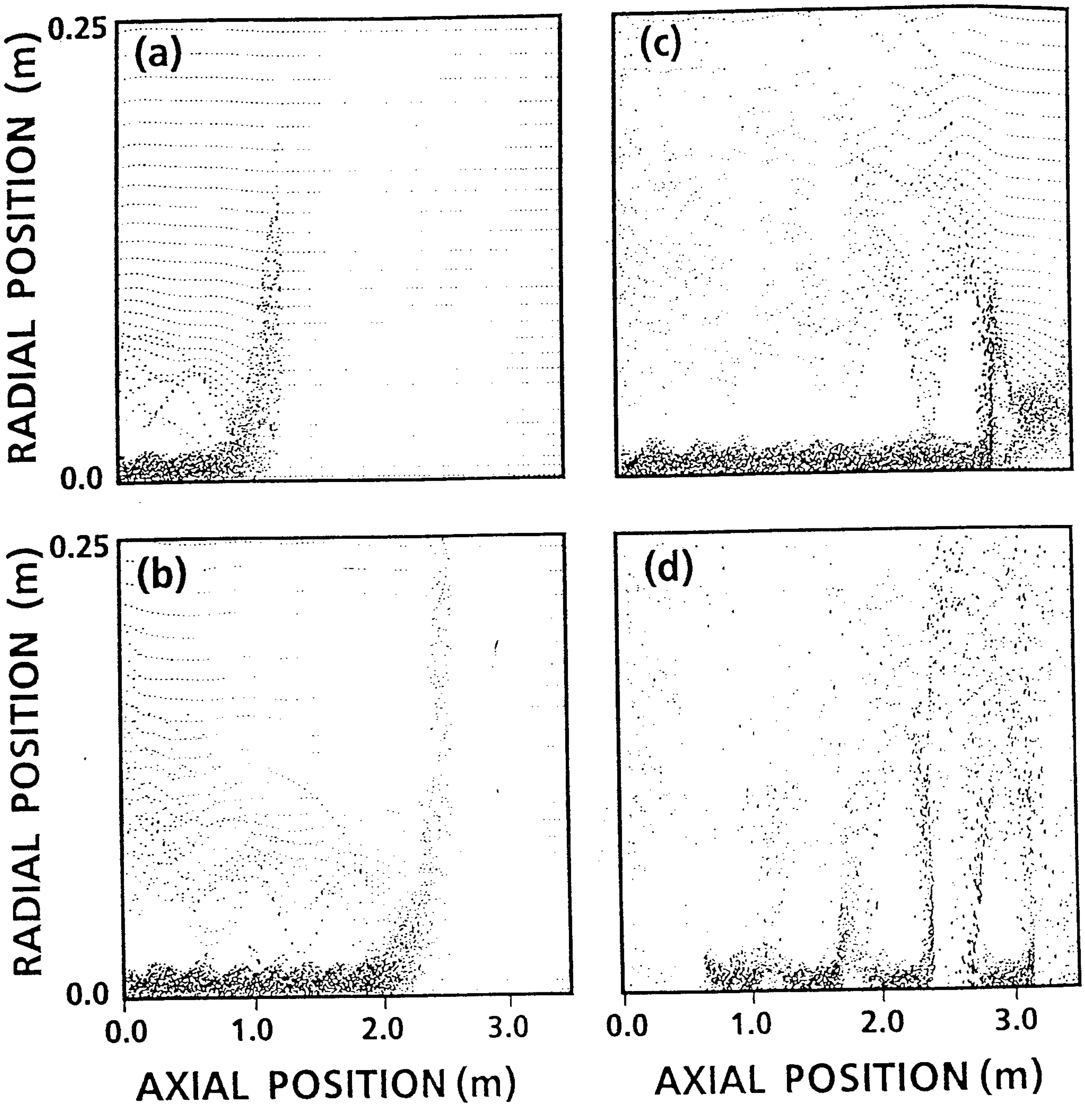
MAGIC SIMULATION PARAMETERS

BEAM: BEAM CURRENT = 1kA
INTIAL RADIUS = 1.5 cm
CURRENT PROFILE: 5 ns RISE, 12 ns FLATTOP, 5 ns FALL
ENERGY PROFILE: TRIANGULAR - 640kV, 1.7MV, 640kV
INITIAL TRANSVERSE TEMPERATURE: 1.65γ keV

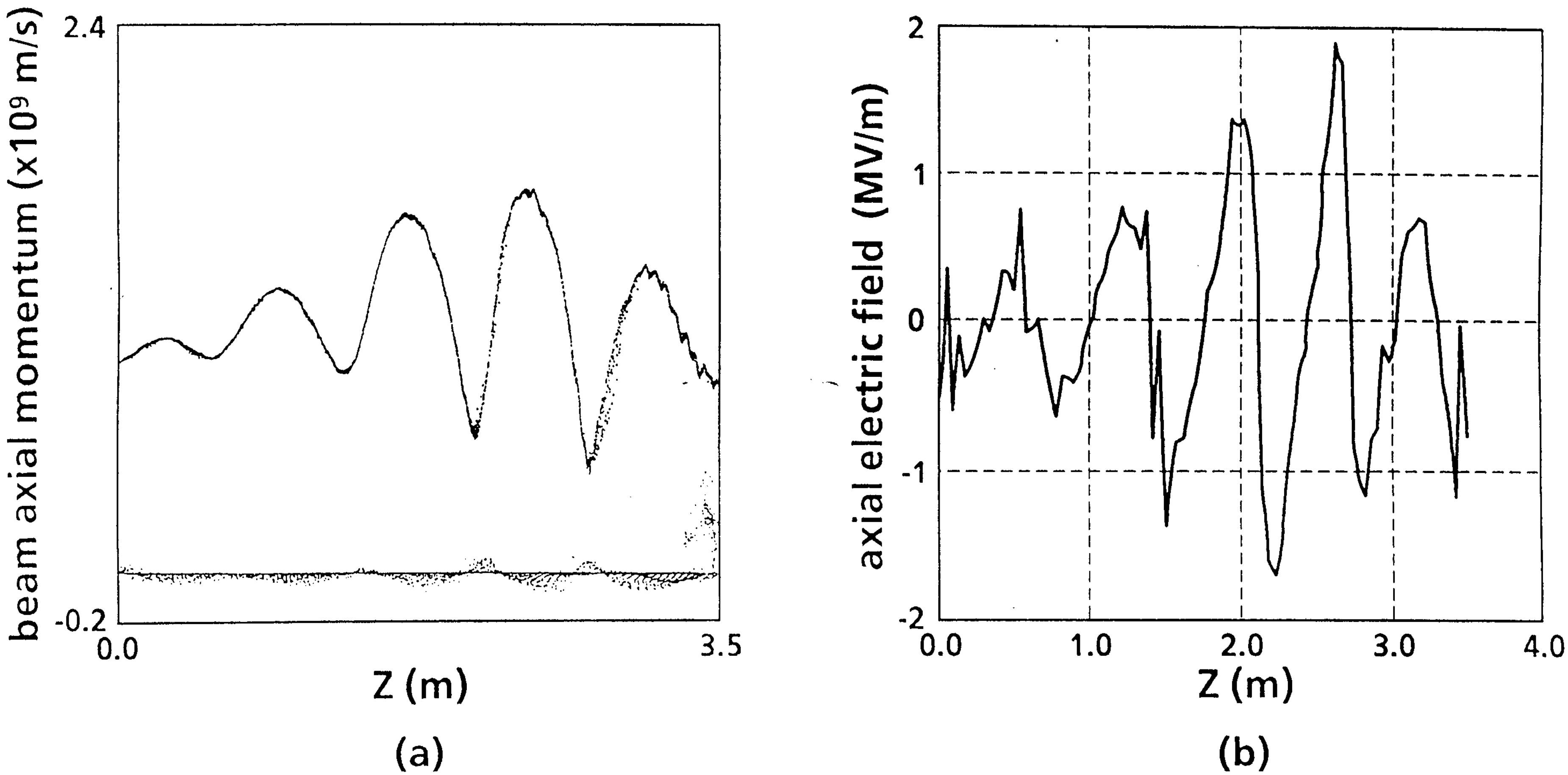
CHANNEL: NEUTRALIZATION FRACTION = 0.8
RADIUS 1.5 CM
SQUARE PROFILE

BACKGROUND PLASMA DENSITY = 2×10^9 cm^{-3}

WAKEFIELD CHAMBER: RADIUS = 25 cm
LENGTH = 3.5 m

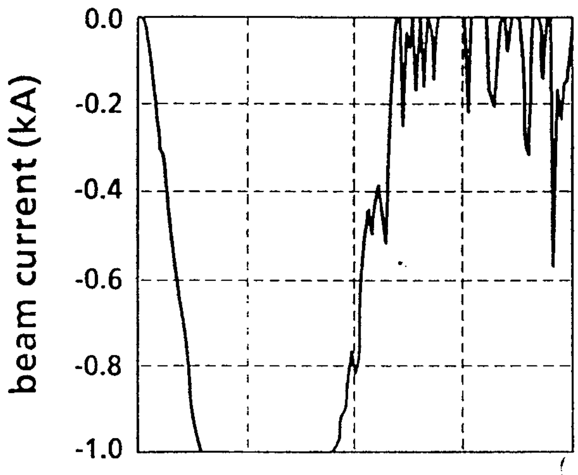


Beam and plasma electron trajectories from MAGIC simulation at (a) t=4.8 ns, (b) t=9.6 ns, (c) t=14.4 ns, (d) t=24.0 ns

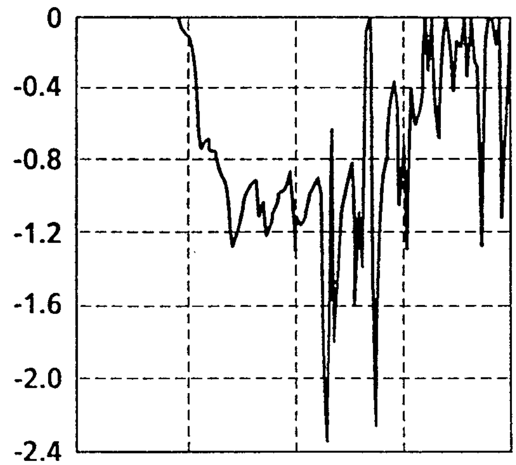


Electron beam axial momentum (a) and the axial electric field (b) at t=19 ns after injection into the plasma-filled transport chamber.

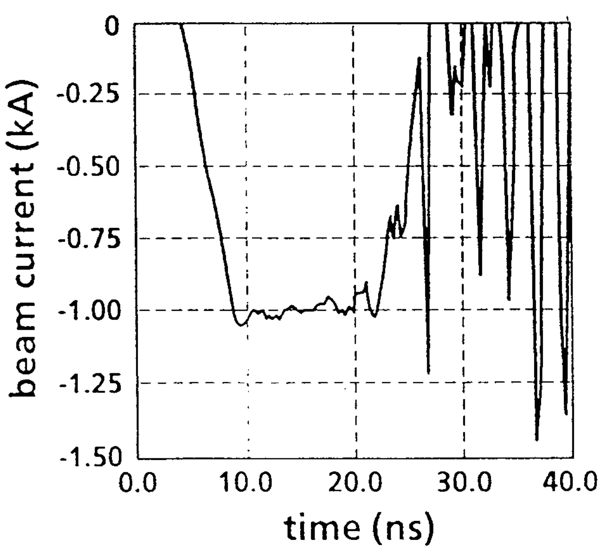
BEAM CURRENT WAVEFORMS FROM THE MAGIC SIMULATION



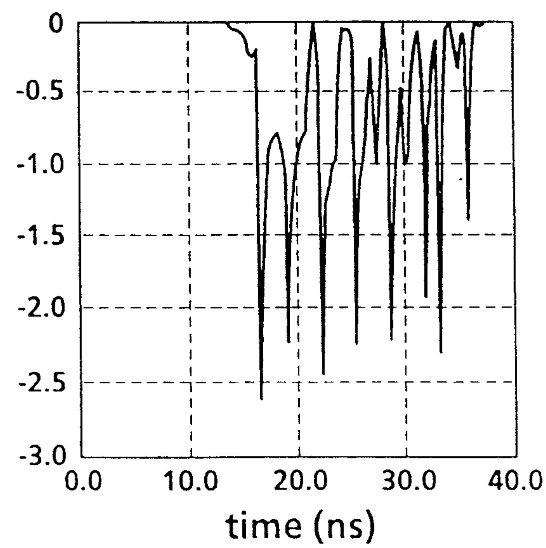
(a) z=0 m



(c) z=2.4 m

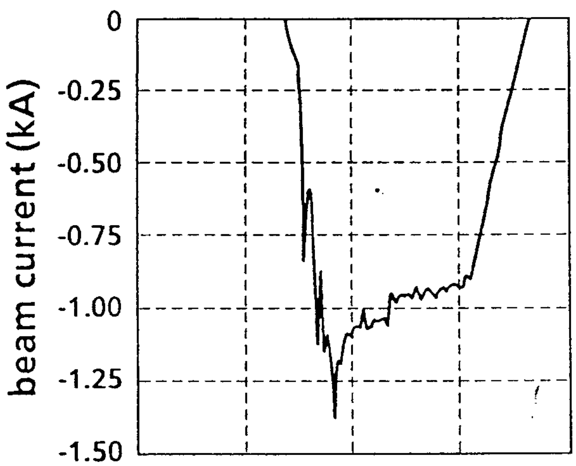


(b) z=1.2 m

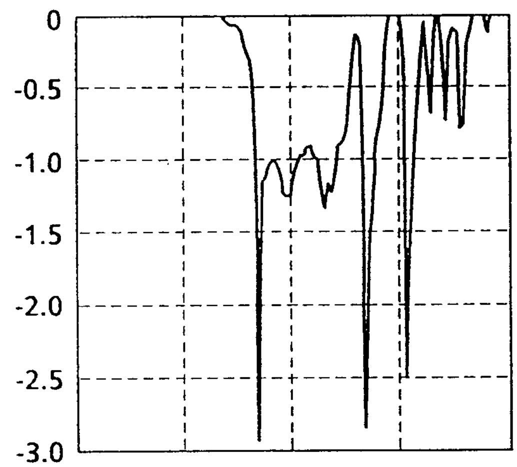


(d) z=3.6 m

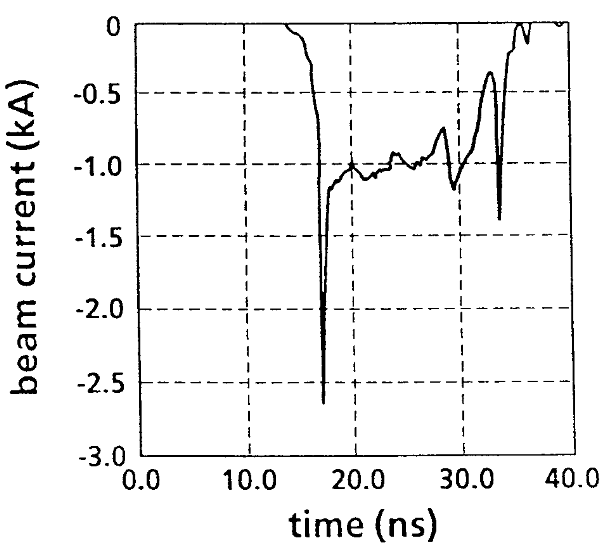
BEAM CURRENT LEAVING THE TRANSPORT CHAMBER FROM THE MAGIC SIMULATIONS



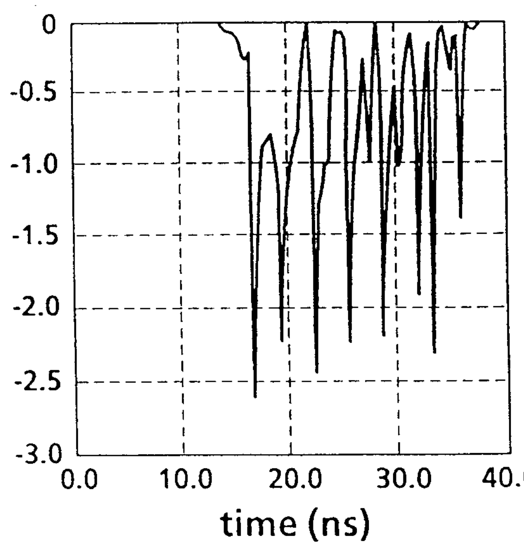
(a) $n_p=0$



(c) $n_p=1.5\text{x}10^9$ cm^{-3}



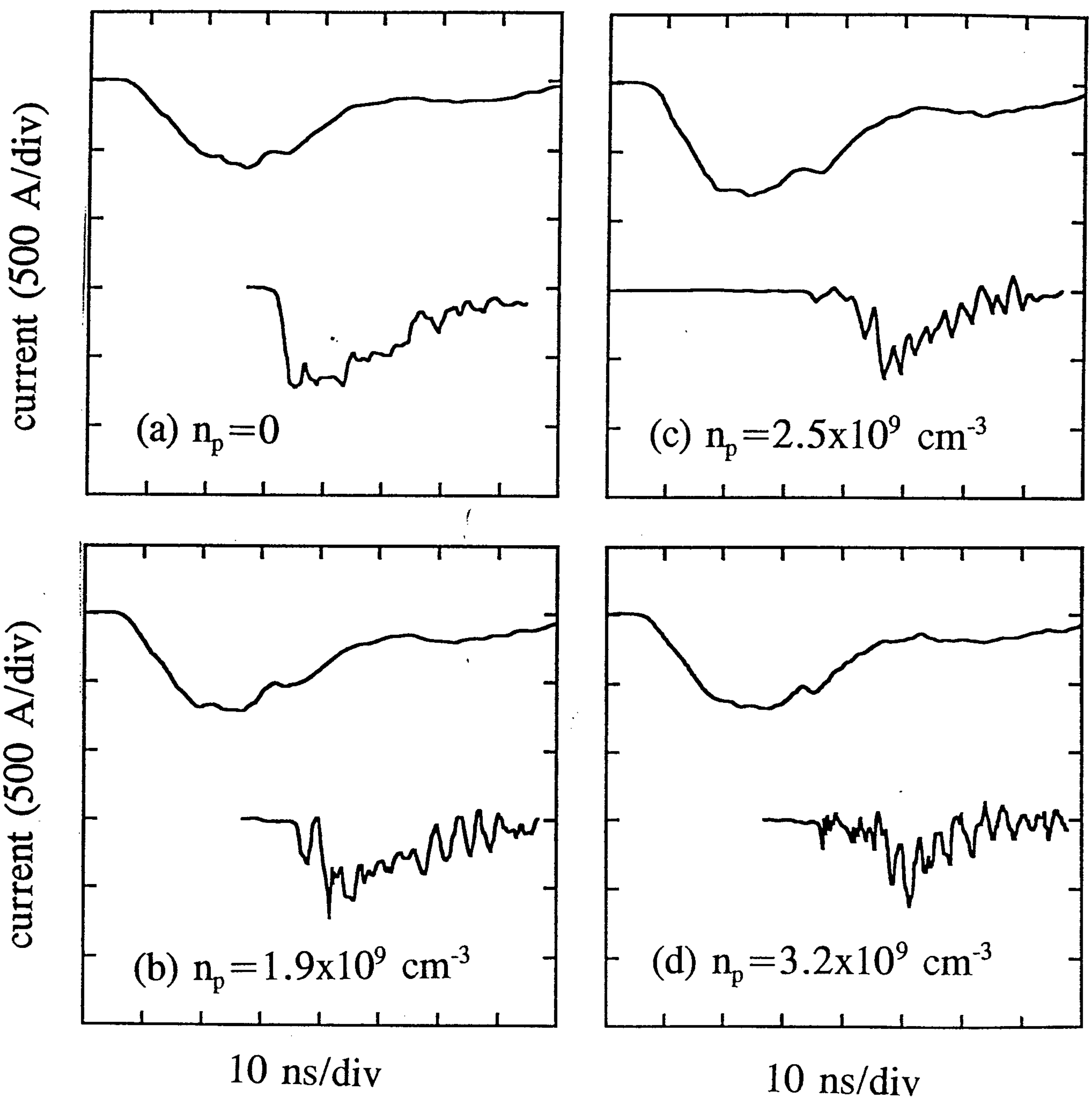
(b) $n_p=1.0\text{x}10^9$ cm^{-3}



(d) $n_p=2.0\text{x}10^9$ cm^{-3}

EXPERIMENTAL CURRENT WAVEFORMS

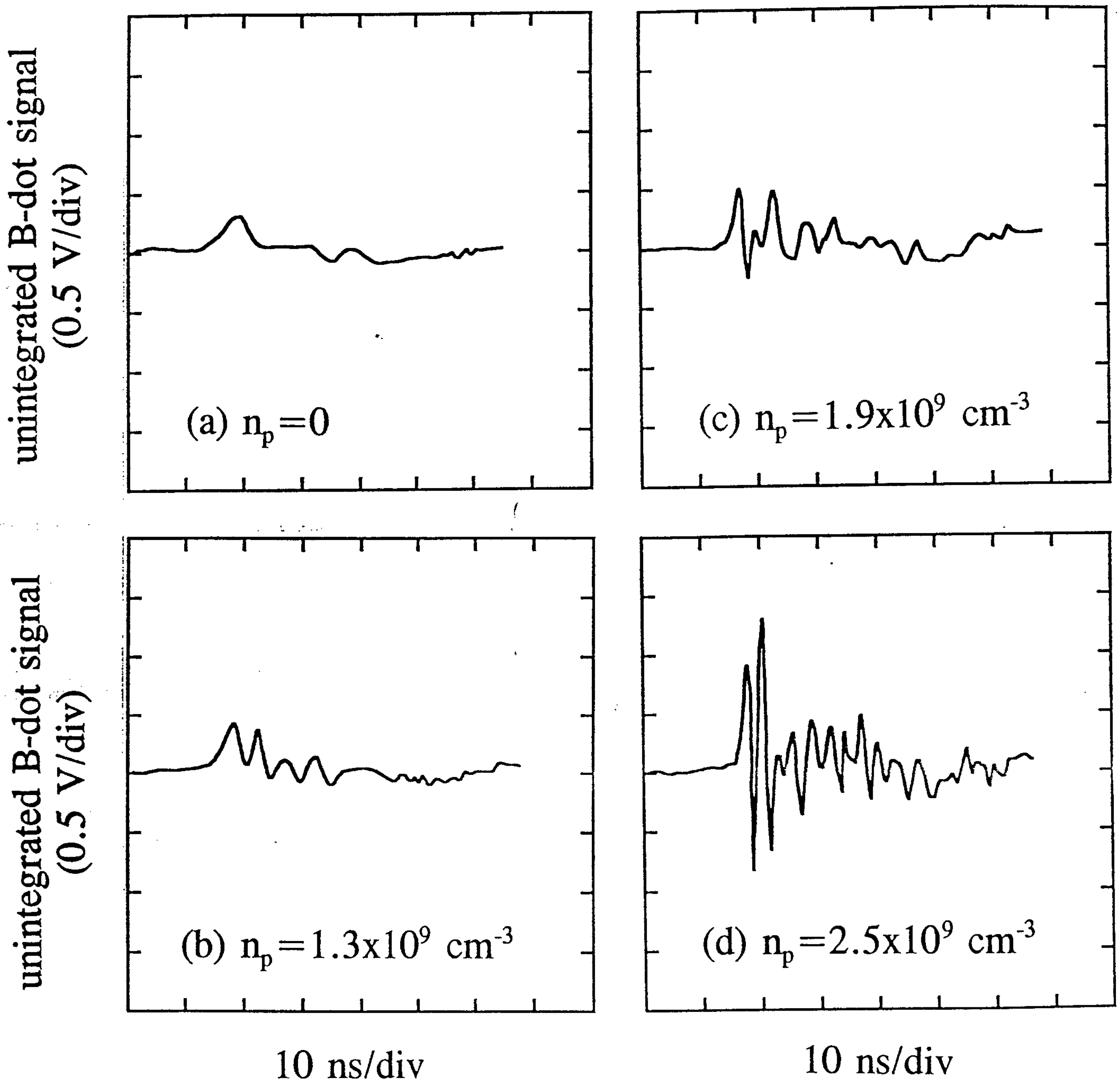
Experimental data: $I_b = 700$ A, $f_e \approx 0.5$



TOP (BOTTOM) WAVEFORM: CURRENT ENTERING (EXITING) THE PLASMA-FILLED TRANSPORT CHAMBER

EXPERIMENTAL B-DOT LOOP RESPONSE

Experimental data: $I_b = 700$ A, $f_e \approx 0.5$



B-DOT LOOP RESPONSE 0.9 M DOWNSTREAM FROM THE ENTRANCE TO THE TRANSPORT CHAMBER

SUMMARY

- Modulation of the beam current due to plasma wakefield effects has been conclusively observed during IFR transport of a high-power REB immersed in a low-density background plasma.

- Good agreement between the experimental results and the MAGIC simulations has been obtained.

- Strong modulation leading to beam current disruption has been observed for plasma density values in the range 1.0×10^9 - 2.0×10^9 cm^{-3} for a 1 kA, 1.7 MeV, 5 ns risetime electron beam after only 3.6 m of beam transport.